Polymer Based Actuators for Virtual Reality Devices

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ABSTRACT

Virtual Reality (VR) is gaining more importance in our society. For many years, VR has been limited to the entertainment applications. Today, practical applications such as training and prototyping find a promising future in VR. Therefore there is an increasing demand for low-cost, lightweight haptic devices in virtual reality (VR) environment. Electroactive polymers seem to be a potential actuation technology that could satisfy these requirements. Dielectric polymers developed the past few years have shown large displacements (more than 300%). This feature makes them quite interesting for integration in haptic devices due to their muscle-like behaviour. Polymer actuators are flexible and lightweight as compared to traditional actuators. Using stacks with several layers of elatomeric film increase the force without limiting the output displacement. The paper discusses some design methods for a linear dielectric polymer actuator for VR devices. Experimental results of the actuator performance is presented.

Keywords: virtual reality, dielectric elastomer, polymer actuator, compliant mechanism, flexures.

1. INTRODUCTION

Virtual Reality (VR) enables users to move and react in a computer-simulated environment. Various types of devices allow users to touch, hear and manipulate virtual objects as if they were real objects. Stationary haptic interfaces have been around for a while and offer good performance. However their working space is limited and their price is quite high. Therefore, there is a serious demand for portable haptic devices. The operator can then navigate and explore the virtual environment without any constraints. Few prototypes based on conventional actuators were developed, however with limited performance specially in terms of weight.

Dielectric elastomers can achieve very large deformations and can deliver relatively large forces when an electric field is applied to them. They have all the advantages of polymers: they are lightweight, inexpensive, fracture tolerant and compliant. All these features make them suitable for actuation applications. However in order to generate a two-way actuator an external spring back force is required. This paper introduces a design of a plastic frame on which the active dielectric polymer is fixed and which acts as the restoring force. The all-plastic actuator presented has potential applications in different fields where weight is a major point of concern. Special emphasis is given to portable virtual reality equipments that need to be light weight and need to deliver enough forces for the force feedback in haptics. Rehabilitation devices will also benefit from this technology.

2. STATE OF THE ART

Dielectric polymers developed the past few years exhibit large displacements (up to 300% ([1,2]) which make them interesting for integration in haptic devices due to their muscle-like behavior. Using stacks with several layers of the elastomeric film increases the force without losing displacement. Dielectric elastomers are lightweight when compared to traditional actuators. Another advantage is their low price and the ease of integration due to their flexibility. The

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possibility to be deposited in thin films and stacked in a multi-layer configuration would allow the miniaturization of these polymer actuators [3]. The driving high voltage electronics is getting smaller and more compact which allows embedded electronics in the device. A high voltage transformer Q50-5 of EMCO which supplies up to 5kV in only 0.125 cubic inches was used to drive the polymer actuators presented in this paper.

Pelrine et al. compared several types of electroactive polymers such as acrylic elastomers and silicones in terms of strain, actuation pressure, time response and efficiency. They proposed different designs for polymer actuators such as stretched films, stacks, rolls, tubes and unimorphs. Potential applications such as microrobots and sound generators could rely on polymer actuators [1]. Wingert et al. introduced a Binary Robotic Articulated Intelligent Device called the BRAID driven by dielectric polymer actuators for future robotic systems, ranging from space exploration to medical devices [4]. The BRAID is a lightweight, hyper-redundant binary manipulator with a large number of embedded actuators. The actuator consists of the polymer film, a flexible frame and a bistable element. The frame applies boundary conditions on the polymeric film in order to enhance the performance without the need of external restoring forces. The bistable element allows the binary driving of the BRAID structure without sensing and feedback control. The frame is deformed and generates a linear motion when a voltage is applied to it. Bar-Cohen introduced the concept of a tactile display using electroactive silicone polymer that contracts while applying an electric field. The aim of such interface as indicated in Fig.1a is to reproduce textual and graphical information for blind persons. This tactile display is a planar array of pins, actuated by electroactive polymers, that creates the tactile output by lowering some pins [2]. Immersion Inc. proposed various haptic interface devices using electroactive polymer actuators for haptic sensations. Human-computer interface devices such as a mouse, joystick, trackball, gamepad, steering wheel, stylus, tablet and pressure-sensitive sphere are introduced [5].

3. APPLICATIONS FOR VIRTUAL REALITY

The main challenge today in dielectric polymer technology is to reduce the high voltages required to drive them. This would be possible when an accurate deposition process would be developed and would allow deposition of thin films of polymer (about 1 µm in thickness) in a multi-layer configuration. Current work at CEA focuses on this issue. This would reduce significantly the high voltages used to drive them and conventional driving electronics could be used in this case.

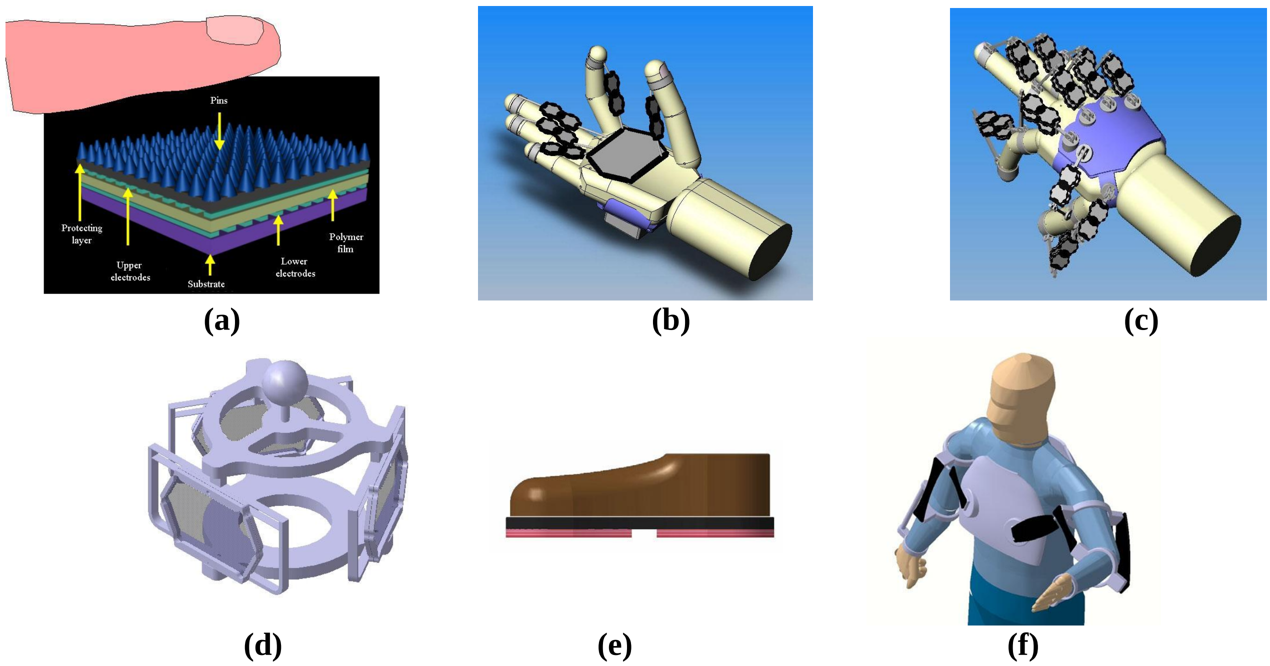


Fig.1. Applications of polymer actuators in virtual reality (a) tactile interface to generate different textures on the finger tip. (b) portable haptic interface mounted on the inner side of the hand (c) another haptic glove design on the finger phalanges (d) a fixed 3-dof haptic interface (e) Haptic shoe (f) Haptic interface to apply a force on the arms.

Current portable haptic interfaces are heavy and cumbersome because they are driven by electric motors. Dielectric polymers are potential actuators to generate different virtual textures through miniature tactile interfaces (see Fig. 1a), to apply forces on the fingers so that the user feels as if he is manipulating virtual objects and being immerged in a virtual environment (see Fig 1b et 1c). The haptic interface might also be a stationary interface such as the parallel robot with 3 degrees of freedom (dof) presented in Fig. 1d. New haptic interfaces might also benefit from the advantages of polymers such as the haptic shoes (see Fig 1e) which would provide different sensations of different grounds with different slopes. Finally haptic interfaces can be used to apply a force on the user's arms and to restrict its motion as indicated in Fig. 1f.

4. DESIGN OF THE ACTUATOR

4.1 Working Principle

The working principle of dielectric polymers can be summarized as follows: an elastomeric polymer film that acts as a capacitor is sandwiched between two compliant electrodes. Two effects occur simultaneously when an electric field is applied between the two electrodes. The polymer is stretched in surface and compressed in thickness during actuation. The change in thickness can be used for mechanical output. However, there is a need to stack many layers of dielectric films and electrodes to obtain large displacements. On the other hand, the area expansion can be used as another method for actuation. The reported strains obtained by pre-stretching the film are much larger than in thickness but a restoring force is required to ensure the desired boundary conditions on the film [6]. This can be achieved either by using an antagonistic pair of actuators or return springs. The following section describes the design of some compliant frames used as a spring back force to generate a two-way actuator.

4.2 Compliant frame (return spring)

As mentioned before a restoring force is needed to use the area expansion of dielectric elastomers in order to create a linear motion and a two-way actuator. In this section the optimization of a flexible structure is described. The polymer with the compliant electrodes on each side is sandwiched between two identical monolithic frames (see Fig. 2). The structure is used to ensure the desired preload boundary conditions and to protect the actuator active material from any damage. In the literature, several flexure elements are described extensively from either the static or the dynamic aspects [7]. In this case, the best implementation would be leaf hinges, circular hinges or elliptic hinges. Extensive work has been carried out in the design of metallic hinges [8], however quite a few publications covered the optimization of polymer based notch flexures.

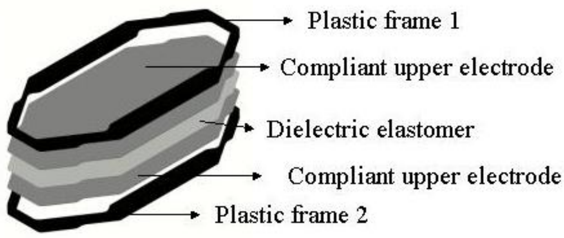


Fig.2. Exploded view of a linear polymer actuator. The compliant structures with leaf strings act as a restoring force to generate a two-way actuator.

4.3 A new design method "FlexIn"

In order to design flexible structures, an experimental toolbox, called FlexIn (Flexure Innovation) has been developed using Matlab at CEA. This method considers a compliant mechanism as an assembly of compliant building blocks. The use of blocks is a natural approach for engineers who can incorporate design experience; for example the designer can define blocks with distributed compliance or blocks with lumped compliance such as notch hinges. The use of blocks reduces the search space and leads to more tractable optimization problems. The blocks have four nodes and are defined with linear beam elements: thus they are not limited to two-connection flexible elements. A multi objective genetic algorithm is used for global optimization of compliant building block assemblies. This new design method is presented extensively in [9].

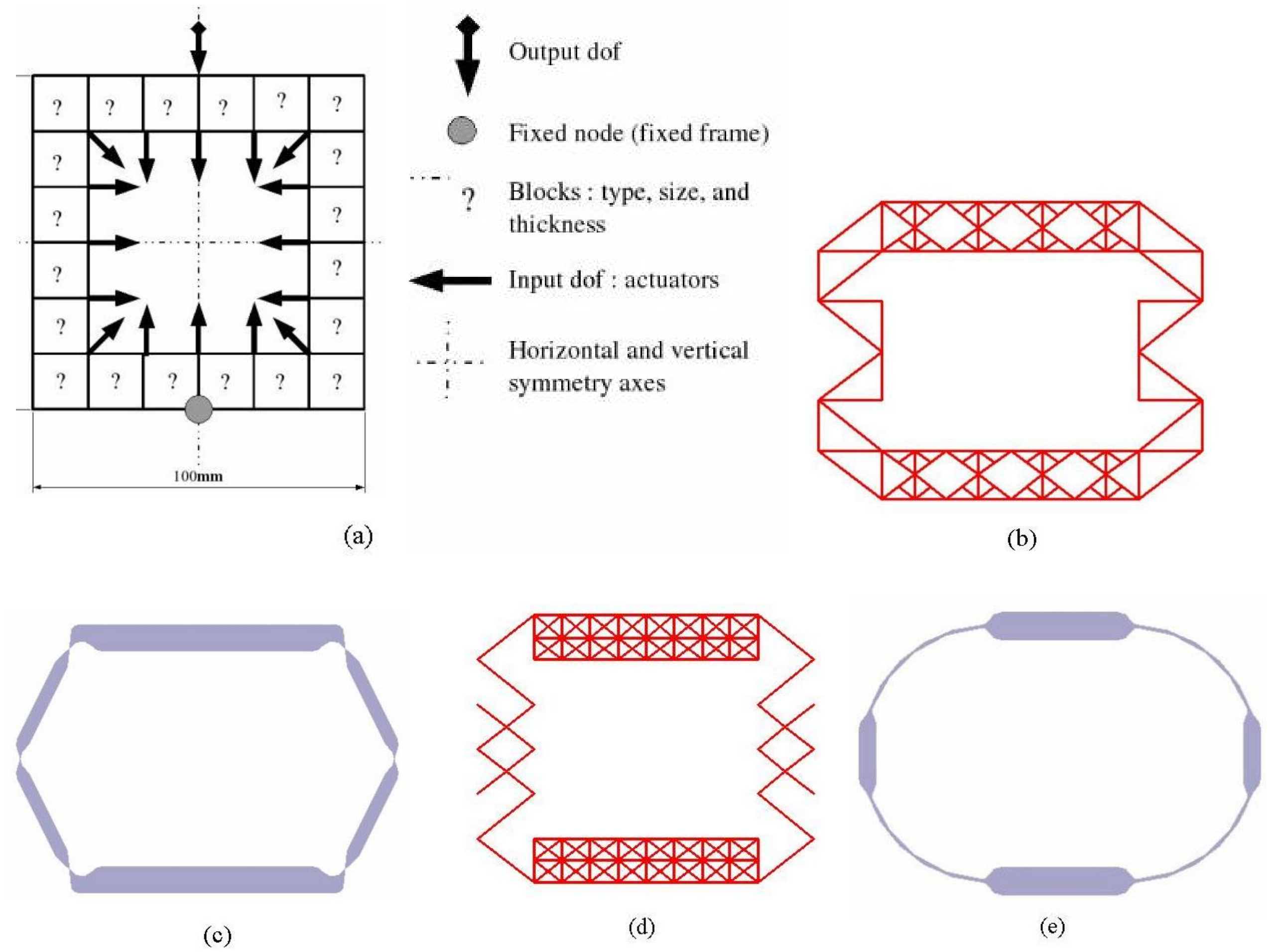
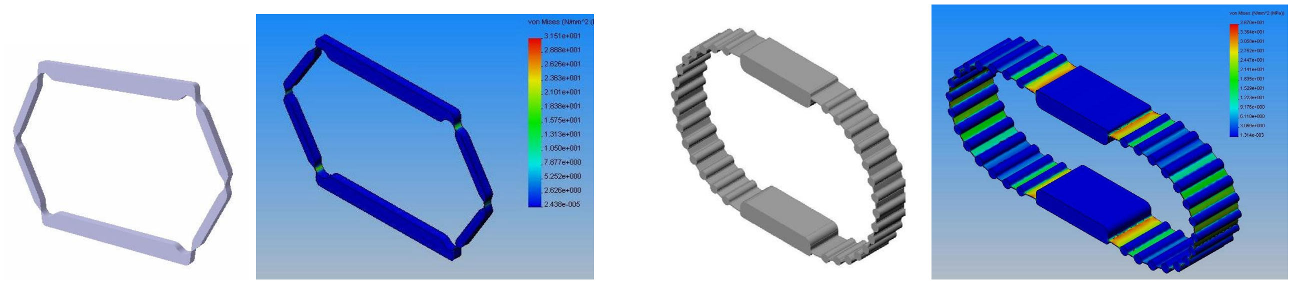


Fig.3. FlexIn: a new design method for compliant structures based on building blocks (a) Initial geometry with the boundary conditions. (b) solution 1 proposed by genetic algorithms. (c) Equivalent compliant structure for solution 1. (d) solution 2 proposed by genetic algorithms. (e) Equivalent compliant structure for solution 2.

The first step consists of specifying the design domain and applying the boundary conditions as shown in Fig. 3a. Design criteria are specified such as the highest stroke/stiffness ratio in the output dof required and the highest stiffness in the orthogonal dof. FlexIn generates a variety of possible solutions as shown in Fig 3b and 3d. Equivalent compliant structures that closely match the solutions and which can be easily manufactured are then proposed in Fig. 3c and 3e.

In the case of the studied frame, it is important to note that further issues should be taken into consideration and which affect the choice of the different solutions proposed by FlexIn. The active part of the actuator which is the dielectric polymer is fixed on the frame. Therefore there should be enough material all over the frame profile to maintain a good adhesion of the polymer on the frame and to prevent any damage that might occur to the actuator. In this case, a solution such as the one presented in Fig 3c would be preferred as the flexibility is concentrated in six notch hinges. However the circular hinges would have limited stroke as compared to leaf springs.

Flexin is aimed to be used as a first design step. Further refinement of the solutions is required in order to fit the applications. Finite Element simulations with CosmosWorks can also be carried out and would act in this case as a confirmation of the first results obtained with Flexin. The two cases introduced in Fig. 3. are considered. It appears from simulation results that case 1 with notch flexures indicated in Fig. 4a and 4b is much stiffer but with a lower stroke than case 2 presented in Fig. 4c and 4d. It is worth noting that in case 2 some cylinders have been added all over the leaf springs to add contact points for the active polymer to adhere. We can therefore expect that a linear actuator that is preloaded with dielectric polymer would generate a larger blocking force in case 1 however its stroke would be smaller than in case 2.



(a) (b) (c) (d)

Fig.4. Different designs for the frame (a) Frame 1: notch flexure design (b) FEA (c) Frame 2: leaf spring design (d) FEA

5. EXPERIMENTAL RESULTS

5.1 Experimental set-up

The frames previously introduced are pre-loaded by the polymer. The polymer used in these measurements was the double-sided acrylic adhesive of 3M (4910). When a voltage is applied, the polymer surface expands and allows the frames to reach their original shape (before applying a pre-load). This is due to the elastic energy that has been released. When the voltage is removed, the polymer pulls the structure back to the pre-strained position. An experimental set-up to measure the force-displacement curves of different frames is shown in Fig. 5. The actuator is fixed at one side and blocked on the other by a load cell to measure the generated force that is connected with a LVDT (Linear Variable Differential Transducer) position sensor. First, the blocking force (0% stroke) is considered. It is the location where the force is at its maximum value. By displacing the load cell with a micro-positioner, the free displacement (no force) output is measured. These two values are the two extreme conditions. Further measurements are taken between the upper and lower limits.

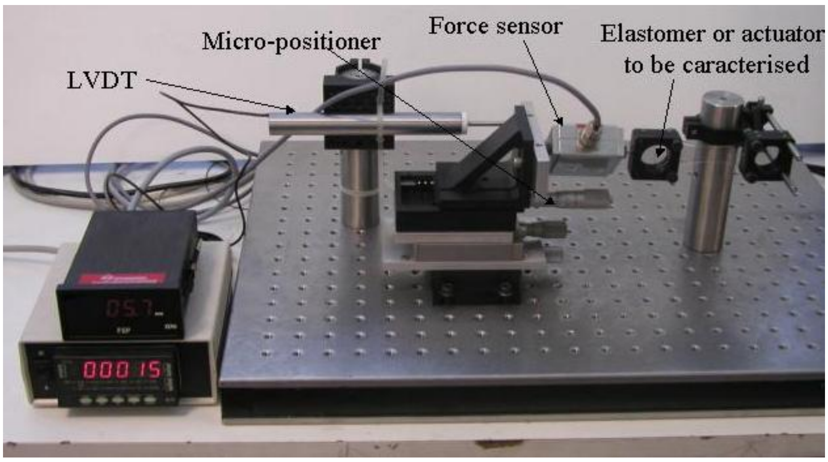


Fig.5. Experimental set-up to measure the force displacement curves of the different actuators design and to determine the stiffness of the active elastomer.

5.2 Force/displacement results

Figure 6 indicates the force/displacement curves for frames with different stiffness due to different geometries of the flexures including frame 1 and frame 2 previously introduced in Fig. 4. The frames are cut using water jet techniques. The material is PolyOxyMethylene (POM) and was chosen due to its good elastic behavior (a high ratio of the maximum stress divided by the Young's modulus: $\sigma max/E$). The dimensions of the two frames are almost similar and can fit in a rectangle of 100 x 40 mm^2 with a thickness of 6 mm for a single frame. Frame 1 can deliver 1.6N at the blocking force position and has a maximum deformation of 14% of its original width. On the other hand, frame 2 delivers a smaller force at zero displacement of about 0.7N, however the deformation reaches 43%.

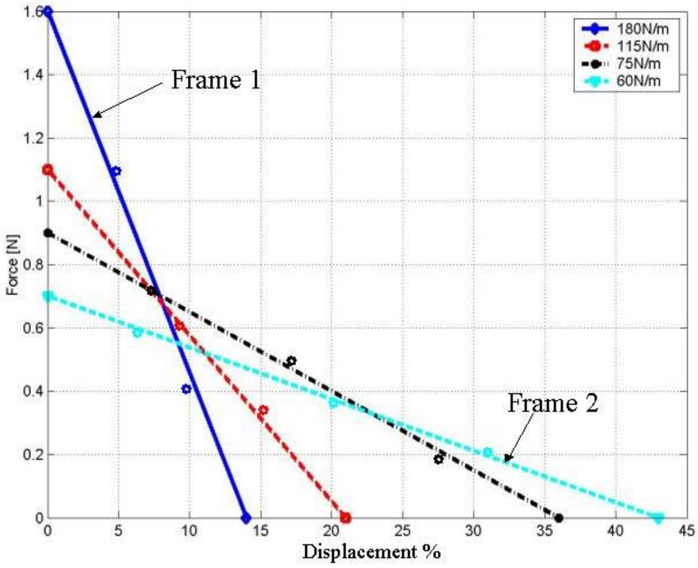


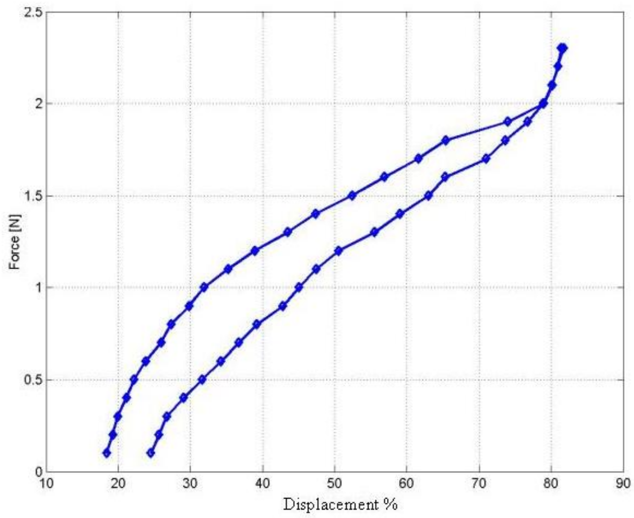
Fig.6. Force displacement curves of polymer actuators with frames of different stiffness.

5.3 Stretching conditions

Determining the stiffness of the acrylic dielectric elastomer is very important as a function of the applied stretching conditions. Stretching the polymer in the two directions is required as the initial thickness of the 3M acrylic adhesive is 1 mm. The electric field required is quite high. Therefore, the polymer thickness should be in the range of 100 µm in order to work with voltages in the range of 5 kV. Experiments were carried out in order to determine the stiffness of the 3M acrylic as a function of the stretching conditions both in the x and y directions. Stretching rate should not exceed more than 400% elsewhere plastic deformation would result (see Fig. 7). Ideally, the frame should be pre-loaded by the acrylic membrane and should maintain a stretching condition of about 250% so that when the field is applied the maximum stretching would reach 400%.

6. FATIGUE TESTS

As the dielectric elastomer actuation technology is still not mature and did not find yet practical applications in commercial products, their life cycle is not well known. Fatigue tests are presented in this work on a linear all-plastic polymer actuator with a maximum stroke of 40% and which delivers forces in the Newton range (see Fig. 8).



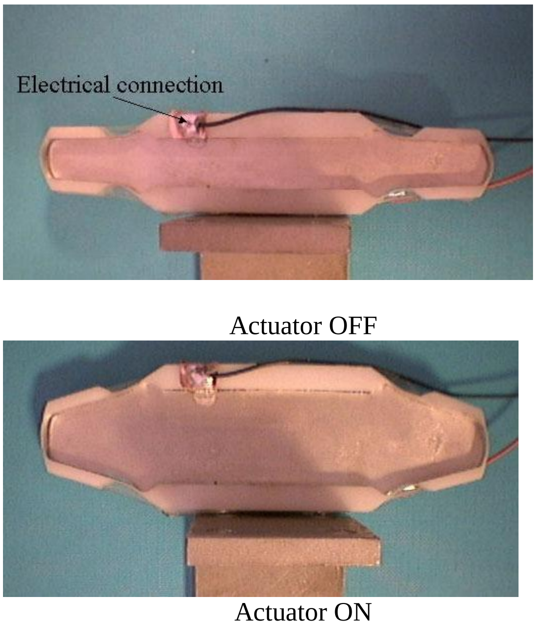


Fig. 7 stiffness of the 3M acrylic is determined. The polymer is stretched by 450% which generates plastic deformation.

Fig. 8. The linear actuator presented has a compliant structure with leaf springs and is deformed by more than 40% when 4kV are applied.

The life duration depends on many parameters such as the stroke, the pre-stretching percentage, the polymer material, the electrodes material, its homogeneity on the polymer surface, and the fixation of the EAP polymer on the plastic frame. Different fatigue tests where carried out at different strokes. The first results look very promising. More than 4 million cycles have been reported (see Fig 9). It is worth noting that the viscoelastic behavior of the acrylic polymer film does not allow the actuator to come back to its original shape even when a low frequency is applied. Fig. 10 indicates the time response of the polymer when 0.25Hz square input of 4kV is applied to it. Most of the failures appeared in the polymer close to the electrical connections as shown in Fig. 8. This is due to the mechanical contact between the Copper strip and the polymer film. A first conclusion from these tests would be that the actuators failed due to the generated stress at this location. This means that when solving this problem the number of cycles should be increased significantly. Current work at CEA concerns more fatigue tests.

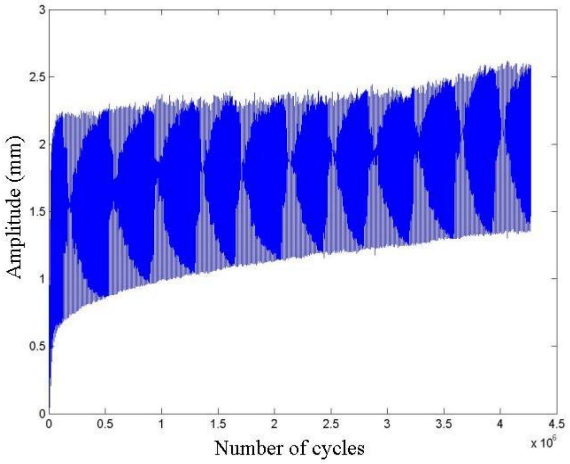


Fig. 9. Fatigue tests.

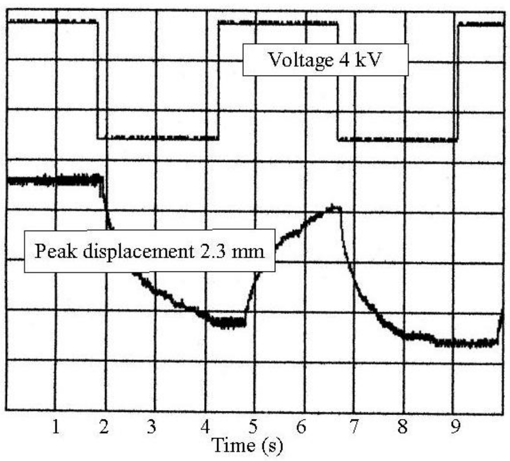


Fig. 10. Time response/ a square input of 0.25 Hz is applied

7. DESIGN OPTIMISATION AND OUTLOOK

By increasing the number of polymer layers, the actuator performance can be improved in terms of force and displacement output. Two alternatives can be considered; the first one is to put several layers directly together and fix them between two flexible frames which are stiffer to compensate the restoring force applied by the pre-stretched elastomeric films. This solution exhibits a polymer fixation problem when number of layers is raised. The second solution might solve this problem by taking also several layers of polymer but separating them with several thinner frames (see Fig.11). A further guiding mechanism composed of four leaf springs can be added to the multiplayer design to rigidify the actuator in the other degrees of freedom.

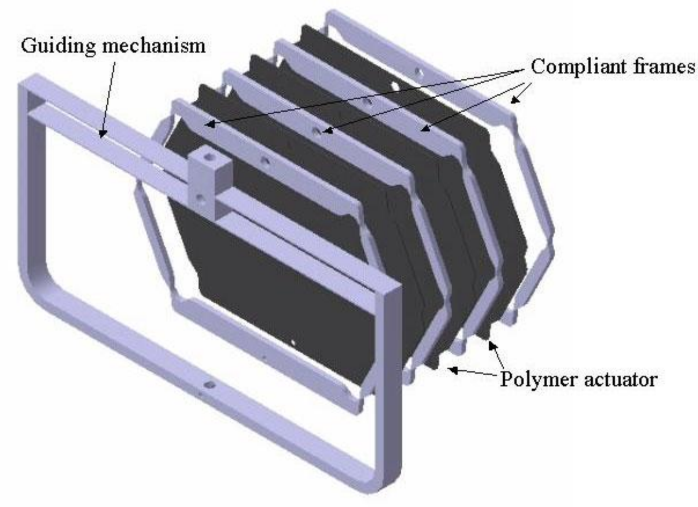


Fig.11. Improved actuator/ increasing the number of layer would increase the generated force.

8. CONCLUSION

This paper presented some design methods for a linear dielectric polymer actuator for Virtual Reality and rehabilitation devices. Different concepts of how to use the electroactive polymer in VR portable and stationary haptic devices and rehabilitation devices are proposed. The optimization of the flexible frame that surrounds the polymer film and that acts as a restoring force to achieve a two-way actuator is presented. This frame is a compliant and monolithic structure made of polymer that has the required properties to be used as flexures. The active polymer is stretched between two compliant frames. In addition to the spring-back force generated, the frame protects the active part, which leads to a more robust actuator. Different designs for the frames are computed through a design method based on genetic algorithms called FlexIn which was developed at CEA. Experimental results of the force-displacement relationship, and the fatigue of these linear actuators are also presented in this work. More than 4 million cycles have been achieved. The failure cause has been detected in the design which means that we can expect much higher life cycles for such actuators. Current work covers this aspect. Finally, a multilayer approach is introduced to increase the delivered force to meet the requirements of haptics. Future work will integrate these linear actuators presented in this paper in portable haptic devices.

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